Ongoing Efforts

Chapel Team, Cray Inc.
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Outline

● **Compiler**
  ● Improving Array Memory Management
  ● Error Handling
  ● Stack Allocate Argument Bundles
  ● Partial Reductions

● **Modules**
  ● Chapel on Intel Xeon Phi “Knights Landing” (KNL)
  ● DefaultRectangular Multi-DData
  ● Mason: A Package Manager for Chapel

● **Applications**
  ● Machine Learning
Ongoing Compiler Efforts
Improving Array Memory Management
Arrays: Outline

● What is the problem?
  ● Array memory management was incorrect and slow

● Why do we have this problem?
  ● Original semantics of arrays required reference counting

● How did we address the problem?
  ● Language changes
  ● Leveraging improved semantics

● What is the result of this work?
  ● Huge reduction in leaks, varied performance impact
Arrays: Background: The Problem

- **Array memory management has been problematic**
  - memory leaks
  - performance overhead

- **Largest source of memory leaks**
  - distributed array leaks account for most leaked data
  - privatized objects are leaked
  - distributions, distributed domains leak as well

- **Significant overhead reduces performance**
  - Array memory management overheads can be surprising:
    ```javascript
    var size = A.domain.size; // changes reference counts!
    ```
  - Benchmarks spend significant time handling array reference counting
    - Have supported a ‘noRefCount’ setting to measure/reduce impact
    - Sometimes dramatic, but guaranteed arrays will be leaked
Arrays: Background: How did we get here?

- **Arrays are implemented to keep arrays alive**
  - when an array slice outlives the original array
  - when arrays are used in begin statements

```plaintext
proc run() {
  var A:[1..100] int;
  begin {
    computeWith(A);
  }
} // local variables normally destroyed here
```

- **And at the same time, to minimize array copies**

- **But…**
  - Implementation erred on keeping arrays alive to the point of leaking
  - Reference counting approach was expensive and overly conservative
  - Language definition did not clearly specify array return behavior
Arrays: This Effort

● To solve these problems we
  ● altered the behavior of returning arrays
  ● leveraged this change to eliminate reference counting

● Lexical scoping eliminates need for reference counting
  ● arrays should be freed when they go out of scope
  ● begin statements need not prevent arrays from being freed
  ● array slices need not prevent arrays from being freed

● Re-implemented array, domain, distribution types to:
  ● remove array reference counting
  ● free distributed objects
  ● rely on fewer special cases in the compiler
Array Challenges: Tuple Improvements

- **Tuple semantics have never been well-defined**
  - a known gap in the language specification
  - CHIP-6 proposed one strategy, but was never finalized or acted upon
  - things have worked “well enough” for this not to receive more attention

- **The array effort ran afoul of issues with tuples**

- **Led us to rework the tuple implementation**
  - Guiding principal: 1-element tuples behave similarly to plain elements
  - implementation is now more direct and straightforward
Array Challenges: Reference Types

- Compiler has longstanding issues with representing ‘ref’
  - inconsistent representations
  - incorrectly identified

- The array effort ran into challenges related to this

- Motivated a new approach: separate ref-ness from type
  - new ‘Qualifier’ IR component
    - ref, const-ref, value, param, unknown, …
    - references now correctly identified, no longer in the type

- Still need to propagate this change through the compiler
  - working our way backwards through the passes

- A positive change independent of arrays work
  - fewer record copies in some cases
  - addresses long-standing pain-point for compiler developers
Arrays: This Effort: Language Changes

- Arrays are now destroyed when they go out of scope
  - begin statements and array slices no longer affect array lifetime

- Arrays return by value by default
  - ref and const ref return intent request alternative behavior
Arrays: Now Destroyed When Out Of Scope

- **Using arrays past their scope is now a user error:**
  ```
  proc badBegin() {
    var A: [1..10000] int;
    begin {
      A += 1;
    }
    // Error: A destroyed here at function end, but the begin could still be using it!
  }
  ```

- **Using a slice after original array destroyed now an error:**
  ```
  proc badSlice() {
    var A: [1..10000] int;
    var slice => A[1..1000];
    return slice;
    // A destroyed here at end of the function, but the returned slice refers to it!
  }
  ```
Arrays: Now Return by Value By Default

● Now the act of returning an array makes a copy:

```c
var A: [1..4] int;
proc f() {
    return A;
}
ref B = f();
B = 1;
writeln(a);
// outputs 1 1 1 1 historically
// outputs 0 0 0 0 after this work
```

● Old behavior available with ref return intent:

```c
proc f() ref {
    return A;
}
```
Arrays: Status

Status:

- Array improvements merged to master on Oct 26th
  - testing reasonably clean, particularly given magnitude of changes
  - graphs on following slides are taken from the next day’s results
- Had hoped to include this in 1.14, but did not feel sufficiently confident
  - it’s a significant change
  - even if it could have been ready in time, wanted to live with it for awhile
- Closes biggest memory leak sources
- Generally improves performance
Arrays: Impact on Leaks

- **Memory leaks were dramatically reduced**
  - Biggest source of memory leaks closed
    - PTRANS benchmark went from leaking 800MB to 0 bytes
  - Distributed arrays no longer leak
    - With the exception of ReplicatedDist (default constructor issue)
Arrays: Impact on Performance

- Substantial single-locale performance improvements

![Graphs showing performance improvements](image-url)
Arrays: Impact on Performance

- Some minor single-locale performance regressions
  - Only one major single-locale performance regression
  - Have not had time to investigate yet
Arrays: Impact on Performance

- Some decent multi-locale performance improvements
Arrays: Impact on Performance

- A few multi-locale performance regressions
  - Root cause still needs to be investigated
Arrays: Next Steps

Next Steps:

- Investigate and resolve performance regressions
  - not surprising that there were a few regressions
  - code was just merged, need some time to investigate
- Close remaining memory leaks
  - issue with generic member variables causing leak with ReplicatedDist
  - undiagnosed leak observed in some applications
  - close non-array-based memory leaks
- Optimize away deep array copies when possible
  - e.g., returning local arrays and assigning result
  - extend this optimization to other record types as well (e.g., ‘bigint’)
- Update language specification to describe:
  - when record/array copies occur
  - tuple semantics in more detail
  - function return is normally by-value
Error Handling
Error Handling: Background

- Chapel lacks a general strategy for handling errors
  - Current approaches: `halt()` and “error” out arguments
  - These are insufficient moving forward

- First cut at an improved design was modeled after Swift

```plaintext
proc canThrowErrors() throws { ... }
do {
  try canThrowErrors();
  try! canThrowErrors(); // will halt on failure
} catch {
  writeln(“first call failed!”);
}
```

- All calls that might throw must be marked with `try`
  - Makes control flow clear with only local information
  - Feedback was that this is too verbose
- Early feedback from users, developers wanted a way to elide `try`
  - e.g., lack of try results in halt-like behavior
Error Handling: This Effort

- Improve the syntax and semantics
  - Streamline for usability
  - Maintain clarity of control flow
- Decide on an implementation approach
- Design document can be found in CHIP #8
Error Handling: syntax and semantics

- Mark error-throwing procedures with `throws`

- Throwing calls must be enclosed by `try` or `try!`
  - Eliminated `do`
  - Defined for single statement and `{ }` blocks
  - Both will attempt to match errors to a `catch` block

- If a matching `catch` is not found:
  - `try` propagates the error
    - To an outer `try`, or out of the procedure (which must throw)
  - `try!` is similar but halts instead of propagating

```plaintext
try {
    canThrowErrors(); // handled by catch on error
    try canThrowErrors(); // propagated to outer try, which goes to catch
    try! canThrowErrors(); // halts on error
} catch {
    writeln(“first call failed!”);
}
```
Error Handling: default and strict mode

- **Tension between convenience and correctness**

- **Default mode**
  - If a throwing procedure is not enclosed with `try`:
    - Halt if that procedure throws an error

- **Strict mode**
  - If a throwing procedure is not enclosed with `try`:
    - Raise a compiler error

- **To start, toggle between modes with a compiler flag**
  - Expect to include a more fine-grained approach in the future
    - Per-module or per-function
Error Handling: errors as classes

● Long-term goal of supporting many types as errors
  ● classes, records, enums, unions, tagged unions, etc.

● To start, all errors must be classes
  ● Implementation convenience
  ● Base class Error will be provided

● catch blocks match against an Error at runtime

```plaintext
try {
  trickyOperation(badArg);
} catch IllegalArgumentError {
  writeln("illegal argument!");
} catch {
  writeln("unknown error!");
}
```

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Error Handling: implementation approach

- Compiler translates into ‘out’ error arguments

// Example: function signatures
proc canThrowErrors() throws { ... }

// translates into
proc canThrowErrors (out _e_out) { ... }

// Example: try-throws
proc caller() throws {
    try canThrowErrors();
}

// translates into
proc caller(out _e_out) {
    var _e: Error;
    canThrowErrors(_e);
    if _e then
        _e_out = _e;
}

// Example: try!
proc handler() {
    try! canThrowErrors();
}

// translates into
proc handler() {
    var _e: Error;
    canThrowErrors(_e);
    if _e then
        halt(_e.message);
}
Error Handling: implementation approach

// Example: try-catch
proc catch() {
    try {
        canThrowErrors();
    } catch {
        writeln(“error occurred”);
    }
}

// translates into
proc catch() {
    var _e: Error;
    canThrowErrors(_e);
    if _e then
        writeln(“error occurred”);
}

// Example: try-catch-throw
proc attempt() throws {
    try {
        canThrowErrors();
    } catch e: SomeError {
        writeln(e.message);
    }
}

// translates into
proc attempt(out _e_out: Error) {
    var _e: Error;
    canThrowErrors(_e);
    if _e then
        writeln(_e.message);
        else if _e then
            _e_out = _e;
}
Error Handling: runtime errors

● **C runtime is independent of Chapel error handling**
  ● Modify runtime to return error codes
  ● Chapel wrapper translates runtime error codes to throws

```plaintext
// Example: in module code
proc chpl_here_alloc(size: int): c_void_ptr throws {
    extern proc chpl_mem_alloc(size: int) : c_void_ptr; // runtime proc
    const p = chpl_mem_alloc(size); // always returns
    if p == c_nil then // runtime says allocation failed
        throw new OutOfMemoryError();
    return p;
}
```

● **More involved implementation**
  ● Will not be included in initial version
Error Handling: error cleanup

- **defer**, Swift’s cleanup construct
  - Runs whenever the enclosing scope exits
  - Cleanup code is local to initializing code
  - Useful outside of error handling

- Chapel will adopt something similar to **defer**

```plaintext
proc caller() throws {
try {
  var a = allocateBigObject();
  defer {
    delete a;
  }
  canThrowErrors(a);
}
}
```

- **More involved implementation**
  - Will not be included in initial version
Error Handling: Status and Next Steps

**Status:**
- Design is hosted on the Github repository as CHIP 8
  - Advertised to the community and solicited feedback

**Next Steps:**
- Implement the design in the compiler
- Release the feature to users in Chapel 1.15.0
Stack Allocate Argument Bundles
Stack Allocate Argument Bundles

**Background:** on/begin/cobegin/coforall create argument bundles
- these argument bundles are heap-allocated in the generated code
- heap allocation can be a significant source of overhead

**This Effort:** compiler generates code to stack-allocate bundles
- the runtime can copy to a heap-allocated region when appropriate
  - in fact, the runtime already does so in many cases because the generated code might free the bundle before it is used
- runtime can identify when a bundle could be destroyed before use

**Impact:** Observed 10-20% speedups for LULESH and MiniMD

**Next Steps:** Complete the change
- nontrivial effort since it touches all tasking and communication layers
Partial Reductions
Partial Reductions: Background

- *Partial* reductions reduce over subset of array dimensions

ex. partial reduction over columns produces a row

| +---+---+---+---+---+---+---+ |
|    |    |    |    |    |    |    | |
| +---+---+---+---+---+---+---+ |
|    |    |    |    |    |    |    | |
| +---+---+---+---+---+---+---+ |

cf. *full* reduction produces a single element

| +---+---+---+---+---+---+---+ |
|    |    |    |    |    |    |    | |
| +---+---+---+---+---+---+---+ |
|    |    |    |    |    |    |    | |
| +---+---+---+---+---+---+---+ |

- Partial reductions are not available in Chapel at present
  - Important for many algorithms, particularly matrix-vector multiplication
  - Can be written manually, but typically at greater expense
Partial Reductions: This Effort – Goals

Design and implement partial reductions

● Candidate syntax:

```javascript
var Q = + reduce only(2) [(i,j) in MatDom] (A(i,j) * P(j));

const C = + reduce only(1,3) myCube;
```

“this is a partial reduction over 2\textsuperscript{nd} dimension”

partial reduction over 1\textsuperscript{st} and 3\textsuperscript{rd} dimensions produces a single column for a 3D array
Partial Reductions: This Effort – Prototypes

Developed templates for compiler to apply

- “Got a partial reduction? Replace it with this piece of code.”
- Implemented partial + reductions of arrays, over a single dimension
- Relies on proposed support within array’s domain map
  - proc dsiPartialDomain() → domain with remaining dimension(s)
  - iter dsiPartialThese() → how to iterate over remaining dimension(s)
  - domain map gets to decide which locales are involved, in what order, etc.

**Basic template**

```c
// implements: result = + reduce only(2) myArray;
forall partIdx in myArray.domain.dsiPartialDomain(exceptDim=2)
do result[partIdx] =
  + reduce myArray.dsiPartialThese(2,partIdx);
```

**“Bulk” template**

- communicate per-locale results in bulk to improve performance
- interface and performance need further development
Partial Reductions: Next Steps

- **Have compiler invoke templates**
  - implement parser changes
  - convert reduction operation into templates
  - avoid creating temporary result if user copies it into an array anyway

- **Generalize to arbitrary expressions, multiple dimensions**

- **Consider bringing ZPL flood/grid dimensions to Chapel**
  - Useful in reduction scenarios for both users and implementers

- **Improve performance**
  - finalize “bulk” template
Ongoing Module Efforts
Chapel on Intel Xeon Phi “Knights Landing” (KNL)
Chapel on KNL: Background

- KNL is a many-core platform (60+ cores).

- Access both to external memory and to on-chip high-bandwidth multichannel DRAM (MCDRAM).

- Presents an opportunity to broaden Chapel’s NUMA support in preparation for more complex architectures.
Chapel on KNL: This Effort

● **We examined MCDRAM performance characteristics**
  ● Experimented with real Chapel code using and not using MCDRAM

● **For many Chapel codes, MCDRAM makes little difference**

● **On two key benchmarks, saw a significant difference**
  ● Streaming: ~50% speedup on tested Chapel code
  ● Random-access: ~20% slowdown on tested Chapel code

● **As a result, we changed our strategy**
  ● We were planning to allow users to ask for “fast” memory
  ● Now we plan to split this into two kinds of “fast”
    ● Streaming
    ● Random Access
  ● Similar to the way the `madvise()` system call works on pages
Chapel on KNL: Status and Next Steps

**Status:**
- Have prototype locale model from previous release cycle
- Gained better understanding of KNL performance characteristics
- Changed plans regarding mechanism of MCDRAM support

**Next Steps:**
- Leverage previous and new insights to enhance NUMA support
- Target KNL in a way that can be used for future architectures
  - KNL Locale Model
  - “Get streaming memory” or “get random-access memory”
- Take advantage of latest Qthreads, with better KNL support
- Work on vectorization improvements/optimizations
  - Also explore potential KNL-specific optimizations
DefaultRectangular Multi-DData
DefaultRectangular Multi-DData: Effort

● **Background:** ‘numa’ locale model doesn’t perform as desired
  ● DefaultRectangular domain and arrays lack sublocale optimizations
  ● domain places tasks as desired (subject to tasking layer limitations)
  ● but arrays have 1 *ddata* data block per node, not explicitly placed
    ● thus: no reliable data/task affinity

● **This Effort:** Localize data as DefaultRect domain does tasks
  for all ... do <*something*>
  
  coforall ... on ... {  // across numa sublocales
  coforall ... on ... {  // across PUs within subloc
    for ... do <part of *something* in subloc’s mem>
  }
  }

● implement *multi-ddata* arrays: 1 *ddata* per sublocale
  ● used whenever locales have sublocales (e.g. numa)
  ● set NUMA/sublocale affinity of *ddata* blocks via OS
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- **This Effort:** Localize data as DefaultRect domain does tasks
  
  ```
  forall ... do <something> ;
  ```
  
  ```
  coforall ... on ... { // across numa sublocales
  coforall ... on ... { // across PUs within subloc
  for ... do <part of something in subloc’s mem>
  }
  }
  ```

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DefaultRectangular Multi-DData: Status

History & Status:

- did not make as much progress as hoped and planned this cycle
- currently working on more principled array index \(\rightarrow\) ddata mapping
  - old: leftmost dim with range \(\geq\) #sublocales, must divide evenly
  - new: same, but without “divide evenly”, \(\pm 1\) index val per ddata block
    (exactly matches task distribution)
- array remote-access data (RAD) opt, bulk I/O, bulk transfer not done

Next Steps:

- finish new index \(\rightarrow\) ddata mapping
- finish RADopt, bulk I/O, bulk transfer
- runtime tasking: implement task placement in qthreads tasking layer
- memory management:
  - numa-awareness in runtime memory layer(s)
  - on Cray X* systems, integrate with use of hugepages
Mason: A Package Manager for Chapel
Mason: Background

- Currently packages are bundled with the rest of Chapel
- A lot of drawbacks and few benefits:
  - Developers must sign a CLA
  - Code must be under a compatible license
  - Chapel core team needs to be involved
  - Packages must serve a wide audience
  - Bound to Chapel’s six month release cycle
- Not ideal for a healthy Chapel ecosystem
Mason: This Effort

- Designed a package management system for Chapel
  - Package manager
  - Build system
  - Package registry

- Trying to avoid reinventing the wheel
  - Shares traits with Rust’s Cargo and homebrew

- Design document can be found in CHIP #9
Mason: Sample Workflow

- **Mason is a command line tool for package management**
  - Also manages project builds

- **Getting started**
  - Initialize the project directory
    ```
    mason new [project name] ...
    ```
  - For project name foo, this produces:
    ```yaml
    Foo/
    Mason.toml
    src/
    Foo.chpl
    ```
  - Write your project code
  - Build your project
    ```
    mason build
    ```
  - In our example, this will compile `Foo.chpl`
Mason: Sample Workflow

● **Dependency management**
  ● Add or remove dependencies
    mason add [package] [version]
    mason rm [package]
  ● Pulled in and included by mason build
  ● Dependency code is downloaded to a common pool of packages

● **Project manifest file**
  ● Mason.toml
  ● Tracks dependencies
    ● Edited automatically by mason
    ● May be edited manually
  ● Stores project metadata
    ● Must be edited manually (name, version, authors, license, etc.)

```toml
[package]
name = "hello_world"
version = "0.1.0"
authors = ["Bradford Chamberlain <brad@chamberlain.com>"]
license = "Apache-2.0"

[dependencies]
Curl = "1.0.0"
```
Mason: Package Registry

● **Implementation**
  ● Github repository of package manifest files
  ● Identical to the one in the project, plus a source url field
  ● Publish a package by submitting a pull request

● **Issues**
  ● Namespacing
    ● First-come, first-served
  ● Versioning
    ● Semantic versioning
  ● Integrity
    ● Travis CI suite
    ● Review board
  ● Licensing
    ● SPDX

```json
[package]
name = "hello_world"
version = "0.1.0"
authors = ["Brad Chamberlain <brad@chamberlain.com>"
license = "Apache-2.0"
source = { git = "https://github.com/bradcray/hello_world", tag = "0.1.0" }

[dependencies]
Curl = "1.0.0"
```
Mason: Implementation Details

● **Lock file**
  ● Mason.lock
  ● “Locks in” a build configuration from the manifest
    ● Serialized DAG of all dependencies
    ● Points to specific Git SHAs
  ● Ensures repeatable builds on other machines
  ● After editing a manifest, generate a new lock
    ● mason update

● **Syncing commands**
  ● mason is a pipeline
    ● source → manifest → lock → dependency code
  ● When mason commands are run, keep them in sync
    ● ex. mason add
    ● triggers mason update, downloaded dependencies
Status:
- Design is hosted on the Github repository as **CHIP 9**
- Advertised to the community and asked for feedback

Next Steps:
- Implement $\texttt{mason}$ in Chapel
- Build and release the first version
Ongoing Application Efforts
Machine Learning
Machine Learning: Background

- **Deep learning frameworks have various limitations/issues**
  - Frameworks support narrow range of parallel & memory architectures
    - Limited by the choice of parallel libraries used in implementation
  - Supporting more architectures requires combining many libraries
    - All with their own syntax and semantics
    - Introduces complexity and burdens framework development
  - Typically written in C/C++
    - Often requiring interface with more productive languages, like Python or R
Machine Learning: Background

● Chapel provides solutions to current issues
  ● Natively supports a wide range of parallel & memory architectures
    ● The list continues to grow
  ● Parallelism expressed under the same syntax and semantics
  ● Chapel is productive and performant
    ● And can still provide interoperate with other languages

● Machine learning is a good use-case for Chapel analytics
  ● Deep learning identified as good area to focus within machine learning
    ● Incredible amount of traction in research & industry
    ● Often requires significant computational resources
    ● Consequently, scalable implementations are necessary
Machine Learning: This Effort

- **Built some toy ML codes**
  - Helped develop an understanding of the basics
  - Helped determine what building blocks are needed in Chapel for ML

- **Identified necessity for high-level linear algebra interface**

- **Created a linear algebra module: LinearAlgebra.chpl**
  - Provides high-level syntax for linear algebra routines
    - Similar in nature to Python’s NumPy or Matlab’s linear algebra interface
  - Built on top of BLAS / LAPACK
    - Users can swap out implementations as needed
    - Could some day be entirely Chapel, as performance permits
Machine Learning: Impact

- **Examples of LinearAlgebra interface:**
  - Matrix-matrix / matrix-vector multiplication: \( \text{dot}(A, B) \)
  - Matrix transpose: \( A^T() \)
  - Matrix inverse: \( \text{inverse}(A) \)
  - Identity matrix: \( \text{eye}({1..10, 1..10}) \)

- **Some toy ML codes built:**
  - Normal Equation
  - Gradient Descent
  - Neural network
    - Creates an N-layer network with any number of neurons per layer
    - Supports stochastic gradient descent with backpropagation
Machine Learning: Status and Next Steps

**Status:** Progress towards machine learning in Chapel

**Next Steps:** Continue to explore ML in Chapel

- Publish Linear Algebra module in 1.15
  - Add additional routines
  - Documentation
  - Integrate BLAS/LAPACK installation with Chapel build system
- Combine existing toy codes into a simple ML framework
- Ramp up toy code implementations, and compare to other frameworks
  - Explore optimizations and parallel implementations
- Work towards a deep learning application
  - Identify or create a benchmark to measure Chapel’s performance
  - Collaborate with researchers on real-world applications
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